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(54) **WIRELESS MAGNETIC FIELD MONITORING IN MAGNETIC RESONANCE IMAGING**

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G01R 33/24	(2006.01)
G01R 33/36	(2006.01)
G01R 33/565	(2006.01)

(52) **U.S. Cl.**

CPC ***G01R 33/243*** (2013.01); ***G01R 33/3692*** (2013.01); ***G01R 33/58*** (2013.01); *G01R 33/56563* (2013.01); *G01R 33/56572* (2013.01)

(58) **Field of Classification Search**

USPC 600/407–435; 382/128–131

See application file for complete search history.

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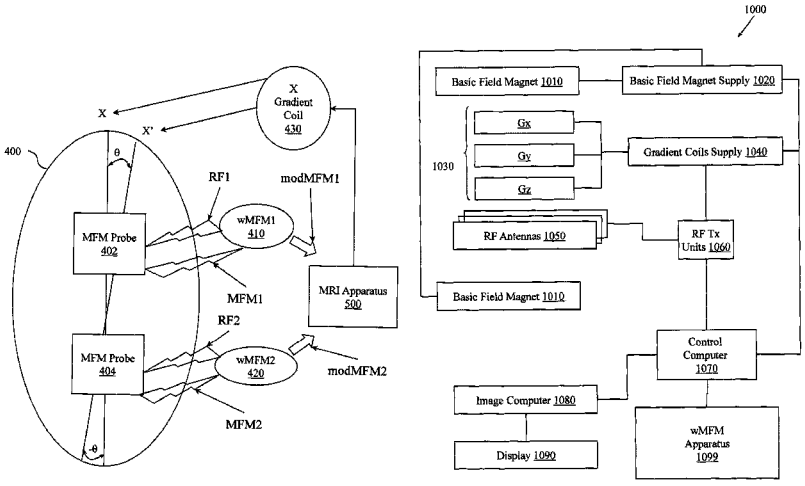
(57) **ABSTRACT**

Apparatus, methods, and other embodiments associated with wireless magnetic field monitoring (wMFM) in magnetic resonance imaging (MRI) are described. One example apparatus includes a wMFM module configured to receive an MFM signal from an MFM probe and to wirelessly transmit modulated MFM signals produced from the received MFM signals to an MRI apparatus. The MRI apparatus is configured with a wireless receiver that receives and processes the modulated MFM signals into information used in an image reconstruction. The MRI apparatus includes an MRI reconstruction logic configured to produce an MR image from the MRI signal based, at least in part, on the magnetic field measurement information.

8 Claims, 13 Drawing Sheets



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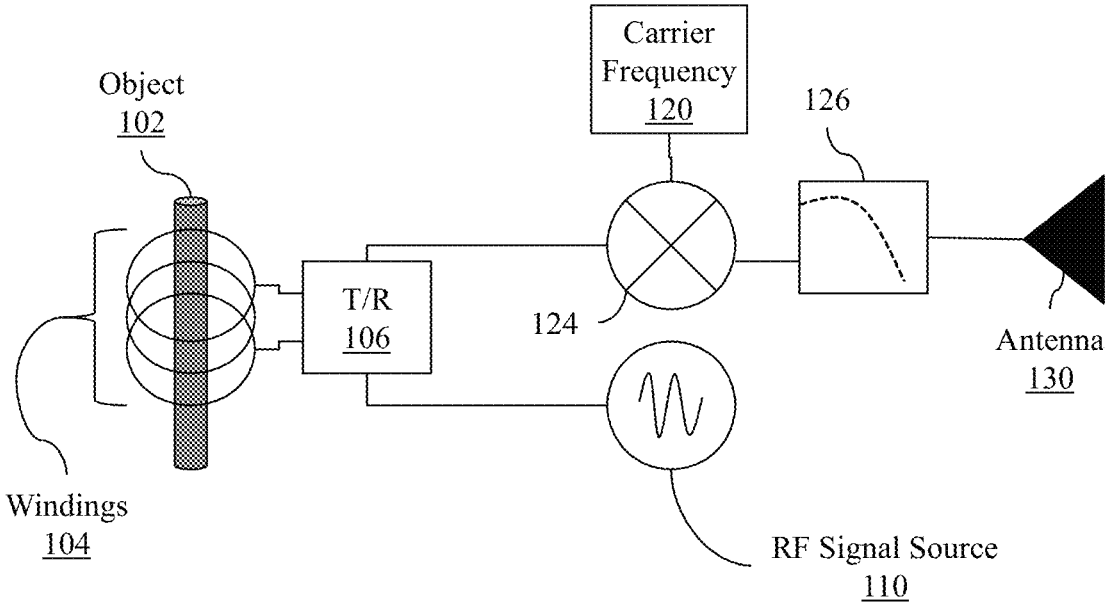
Object
102
Carrier
Frequency
120
126
T/R
106
124
Antenna
130
Windings
104
RF Signal Source
110

Figure 1

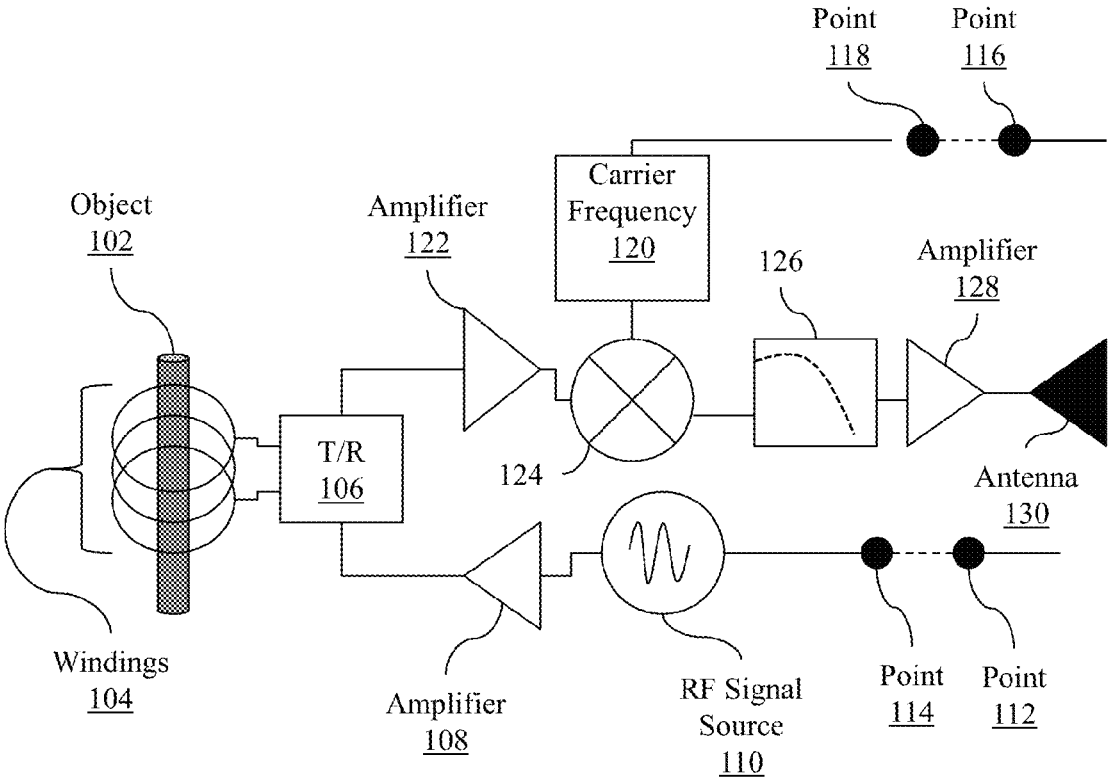
Point
118
Point
116
Carrier
Frequency
120
Object
102
Amplifier
122
126
Amplifier
128
T/R
106
124
Antenna
130
Windings
104
Amplifier
108
RF Signal
Source
110
Point
114
Point
112

Figure 2

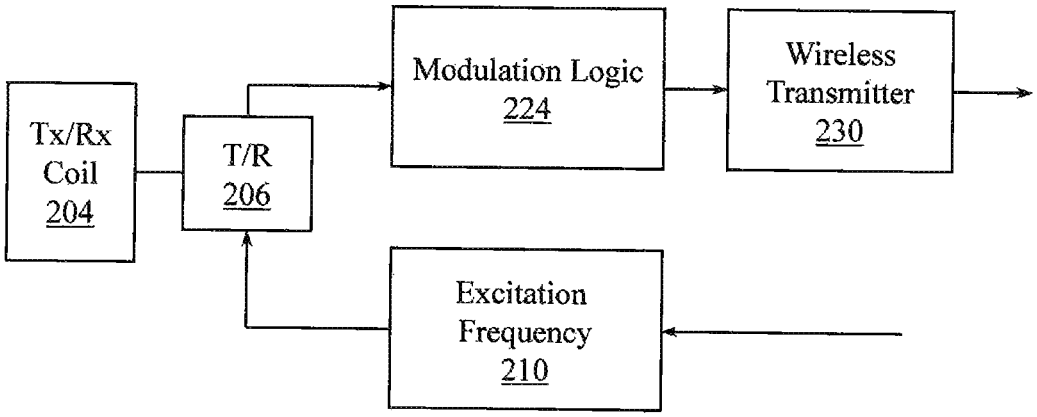
Tx/Rx
Coil
204
T/R
206
Modulation Logic
224
Wireless
Transmitter
230
Excitation
Frequency
210

Figure 3

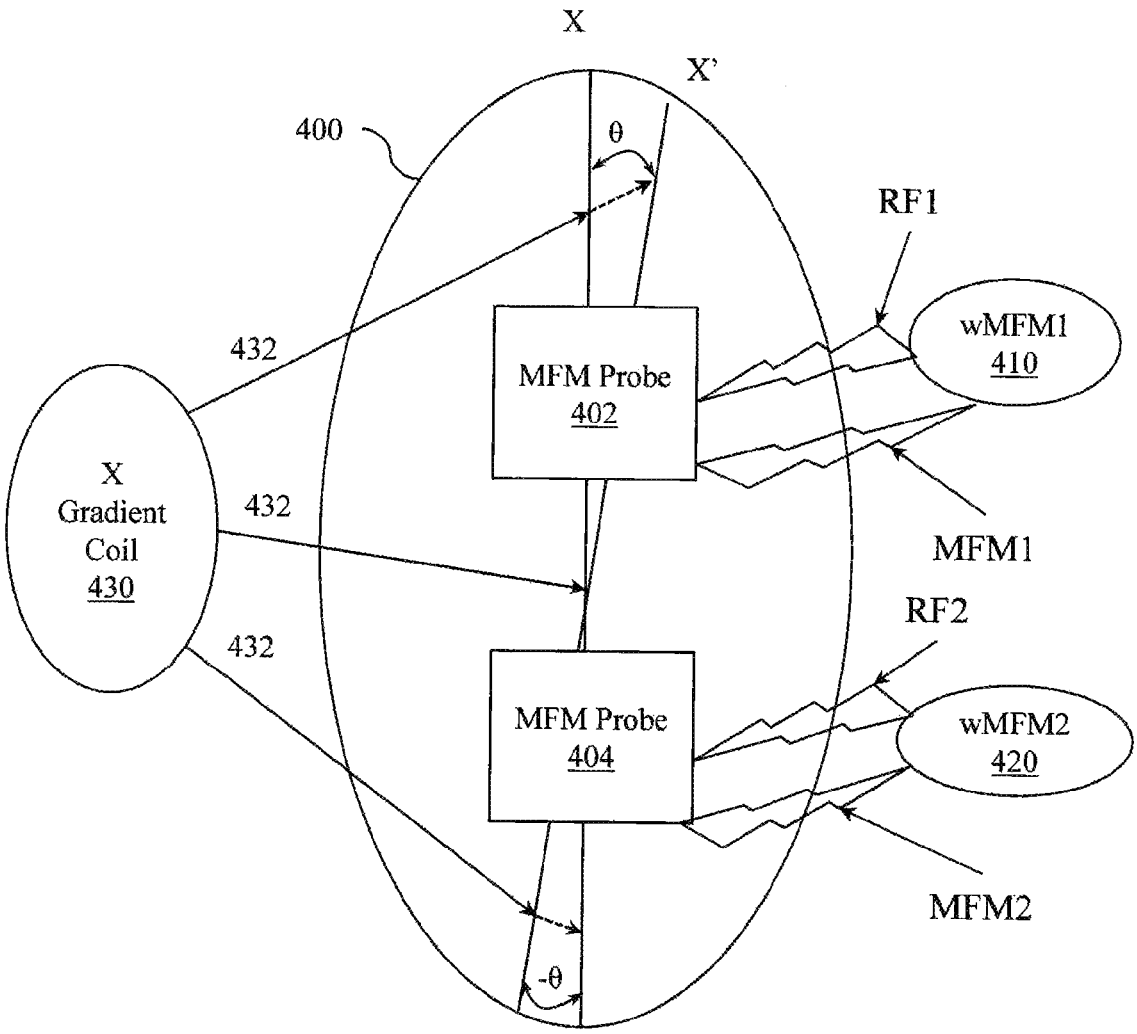
X
X'
400
θ
RF1
wMFM1
410
MFM Probe
402
432
X
Gradient
Coil
430
432
MFM1
RF2
432
MFM Probe
404
wMFM2
420
MFM2
-θ

Figure 4

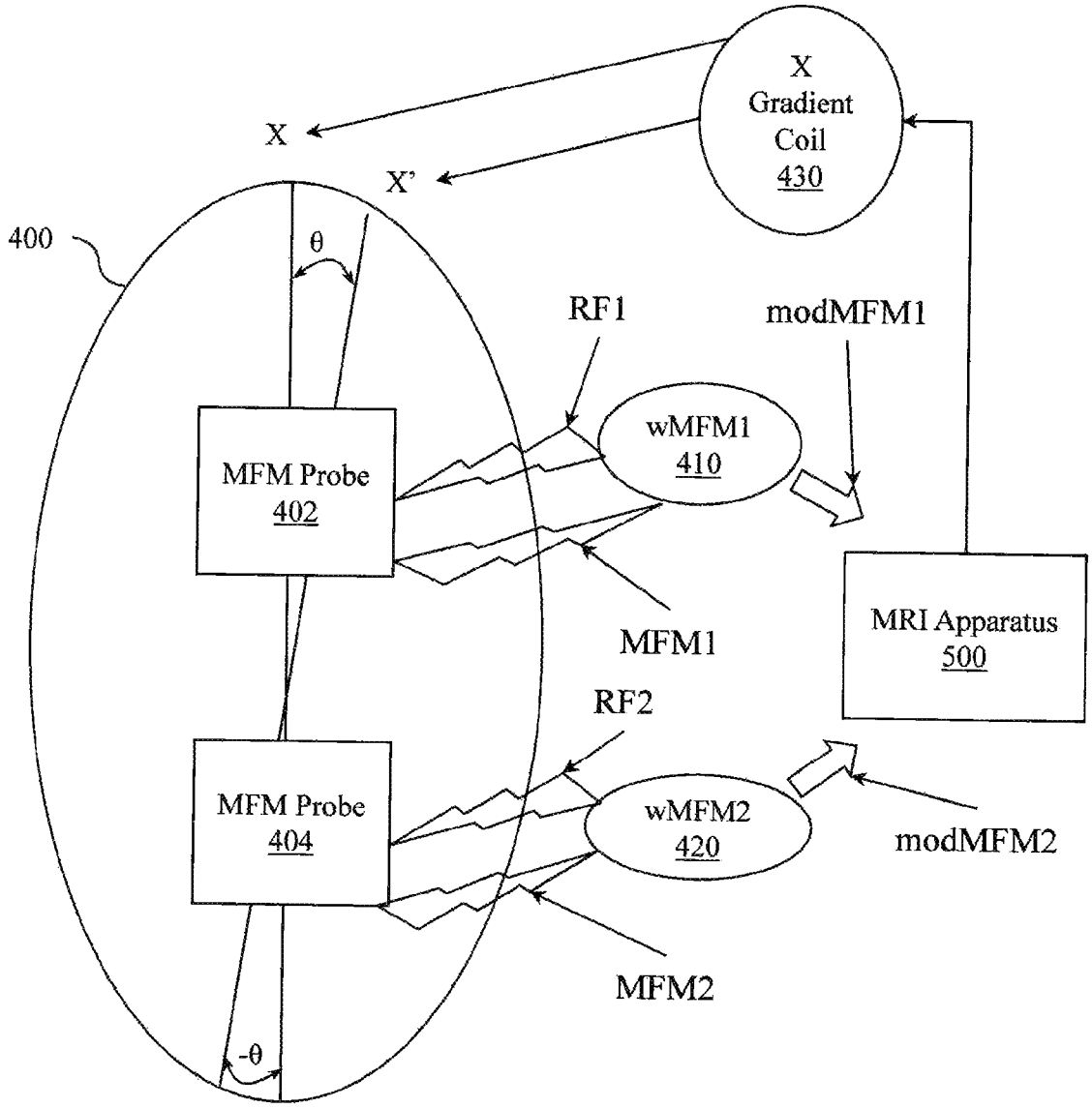
X
Gradient
Coil
430
X
X'
400
θ
RF1
modMFM1
wMFM1
410
MFM Probe
402
MFM1
MRI Apparatus
500
RF2
MFM Probe
404
wMFM2
420
modMFM2
MFM2
-θ

Figure 5

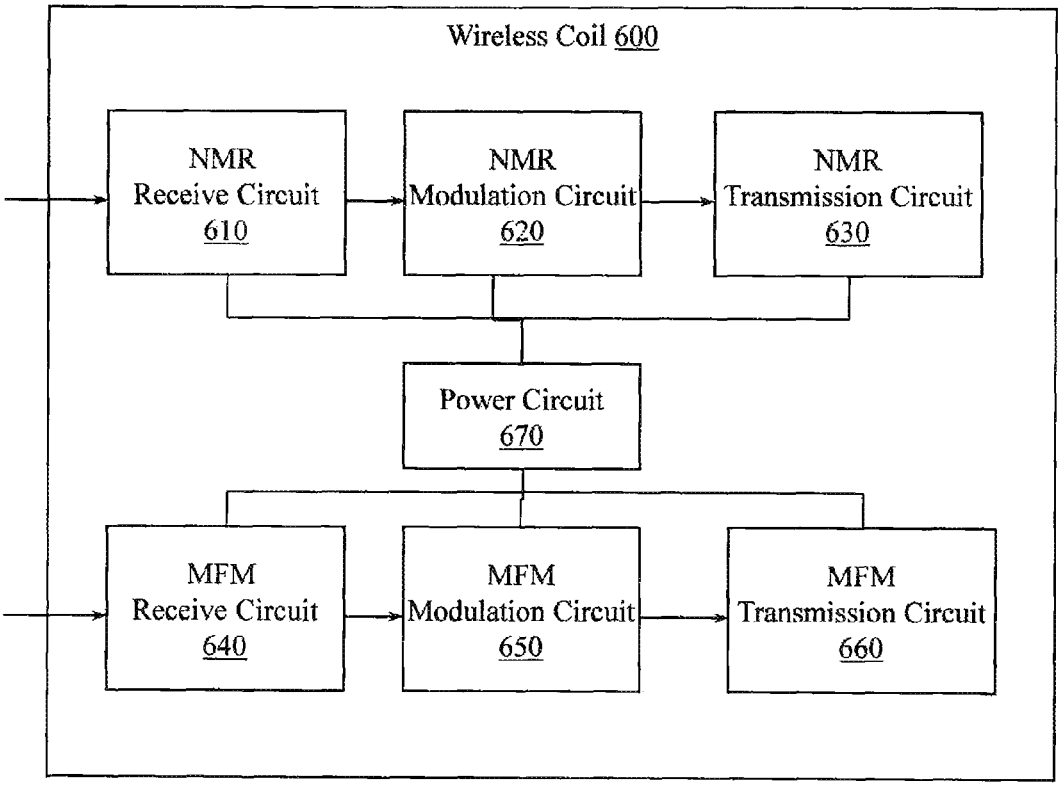
Wireless Coil 600
NMR Receive Circuit 610
NMR Modulation Circuit 620
NMR Transmission Circuit 630
Power Circuit 670
MFM Receive Circuit 640
MFM Modulation Circuit 650
MFM Transmission Circuit 660

Figure 6

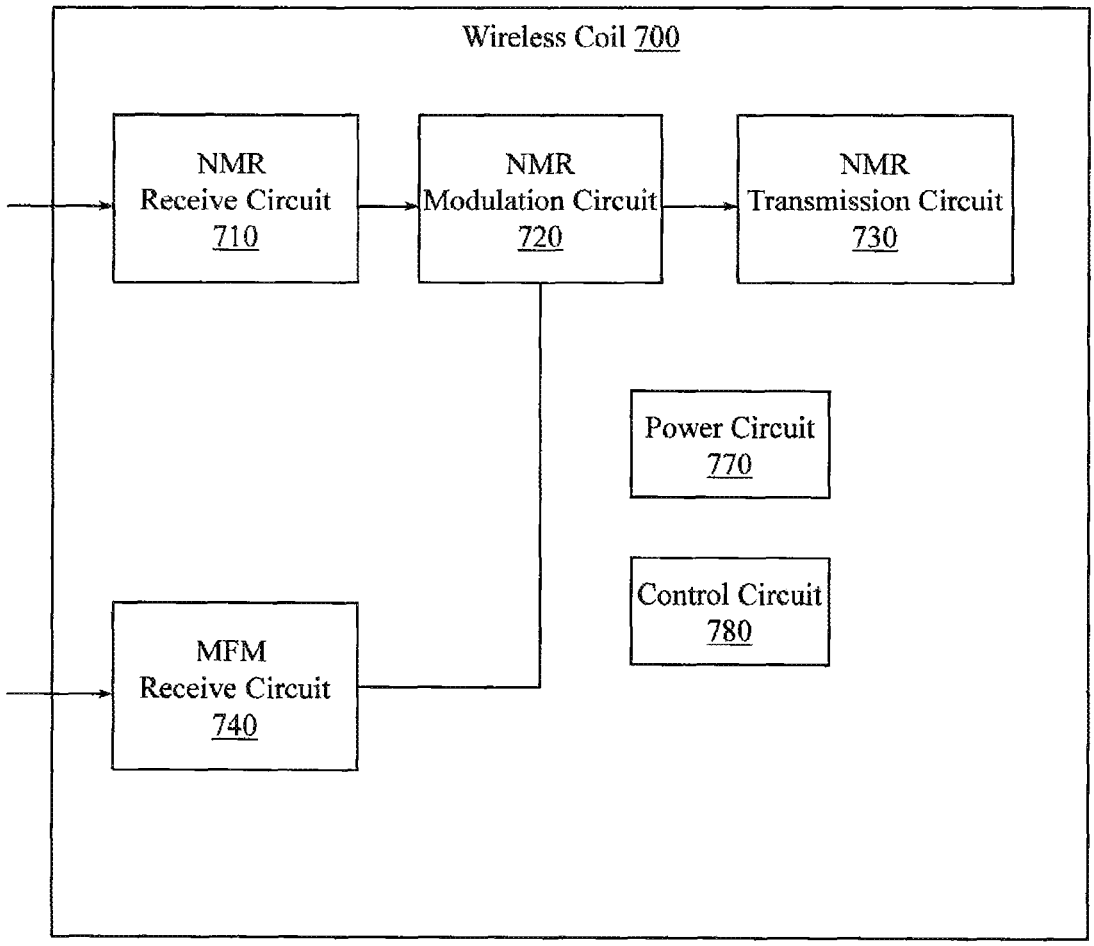
Wireless Coil 700
NMR Receive Circuit 710
NMR Modulation Circuit 720
NMR Transmission Circuit 730
Power Circuit 770
Control Circuit 780
MFM Receive Circuit 740

Figure 7

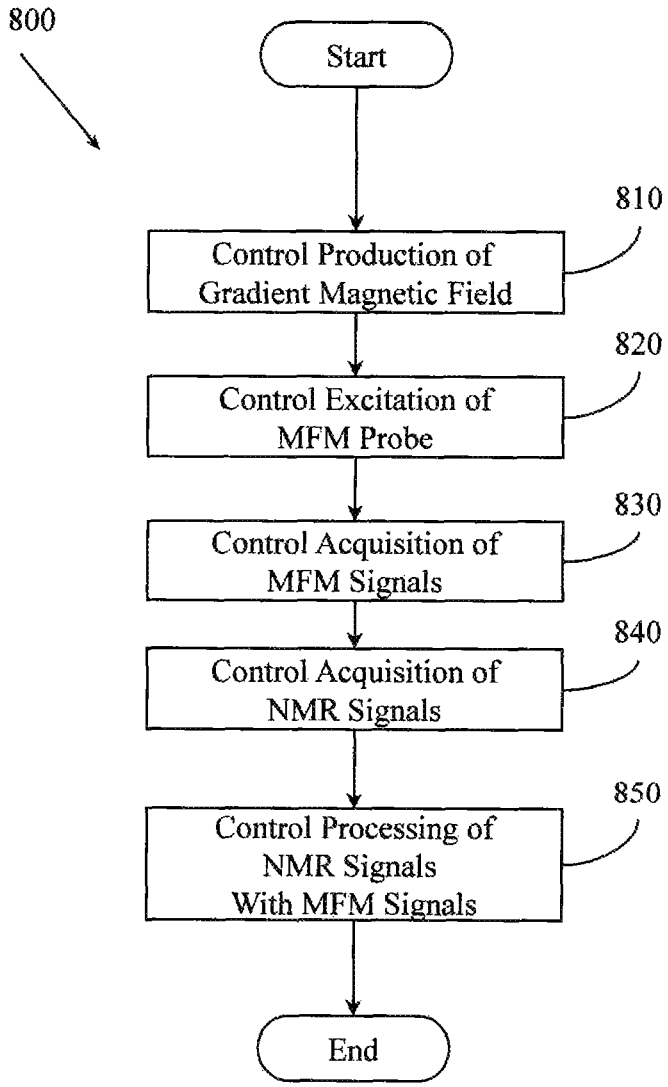
800
Start
810
Control Production of Gradient Magnetic Field
820
Control Excitation of MFM Probe
830
Control Acquisition of MFM Signals
840
Control Acquisition of NMR Signals
850
Control Processing of NMR Signals With MFM Signals
End

Figure 8

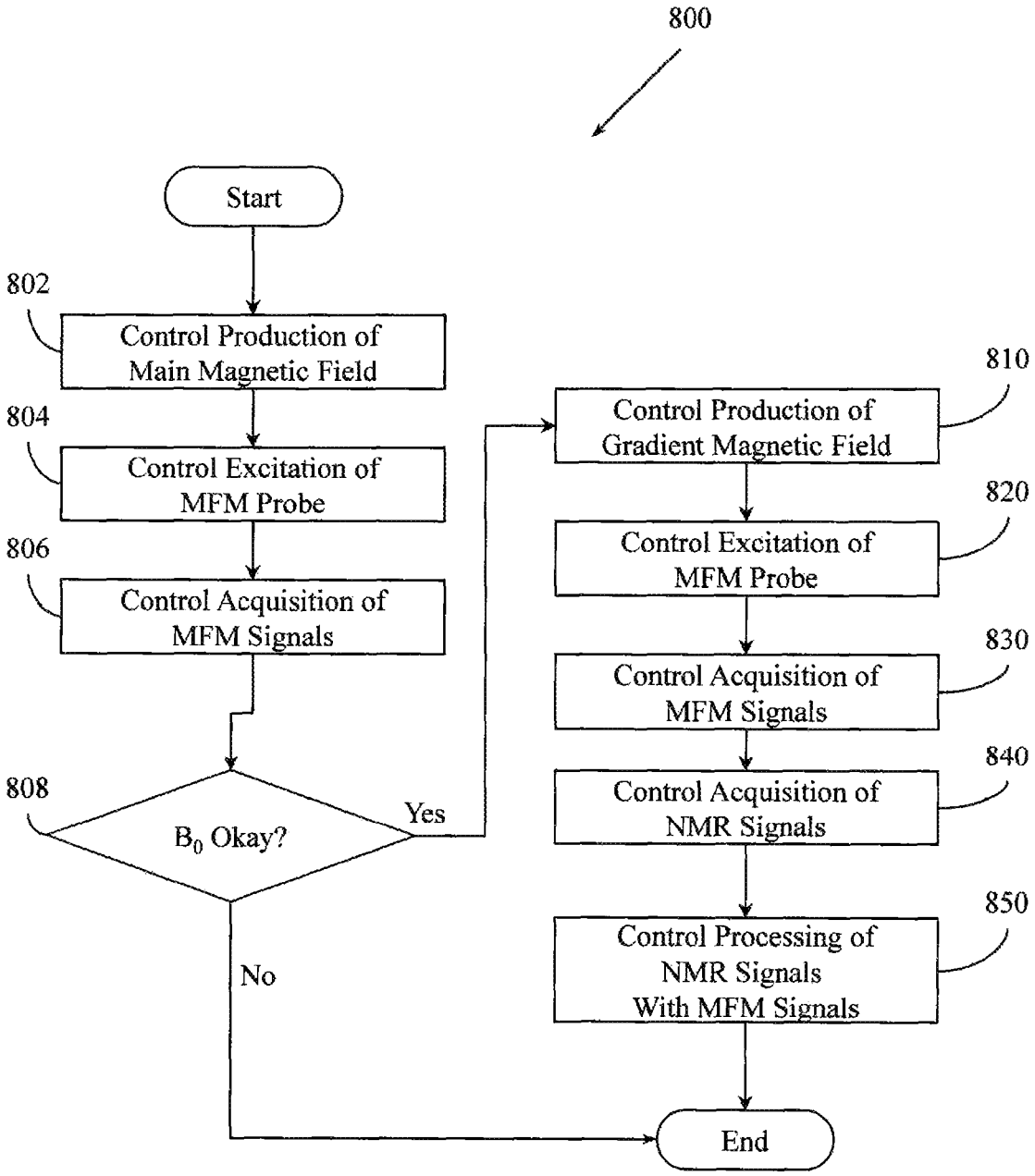
800
Start
802
Control Production of Main Magnetic Field
804
Control Excitation of MFM Probe
806
Control Acquisition of MFM Signals
808
B_0 Okay?
Yes
No
810
Control Production of Gradient Magnetic Field
820
Control Excitation of MFM Probe
830
Control Acquisition of MFM Signals
840
Control Acquisition of NMR Signals
850
Control Processing of NMR Signals With MFM Signals
End

Figure 9

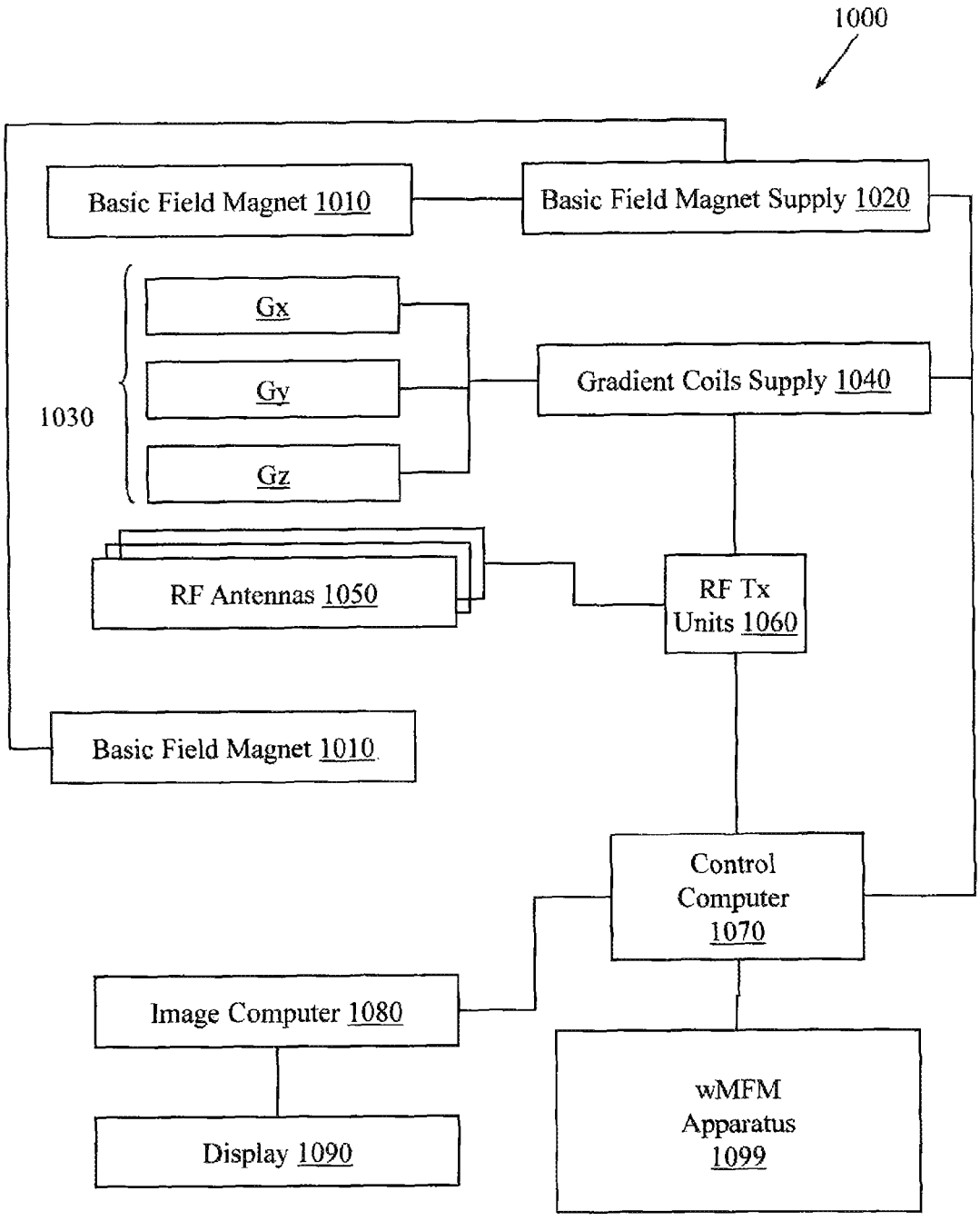
1000
Basic Field Magnet 1010
Basic Field Magnet Supply 1020
Gx
Gy
Gz
1030
Gradient Coils Supply 1040
RF Antennas 1050
RF Tx Units 1060
Basic Field Magnet 1010
Control Computer 1070
Image Computer 1080
Display 1090
wMFM Apparatus 1099

Figure 10

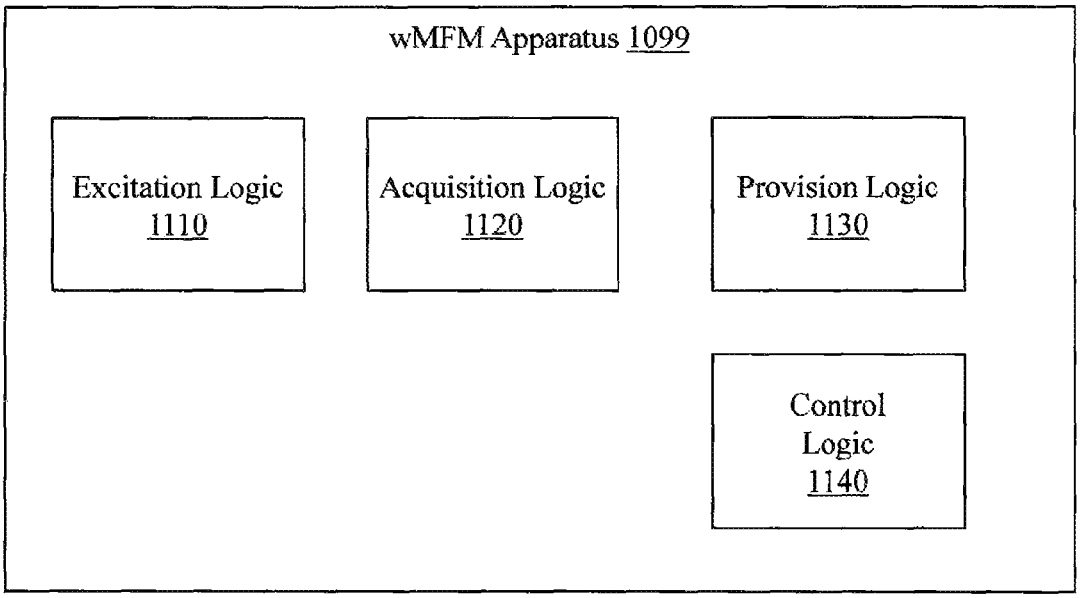
wMFM Apparatus 1099
Excitation Logic 1110
Acquisition Logic 1120
Provision Logic 1130
Control Logic 1140

Figure 11

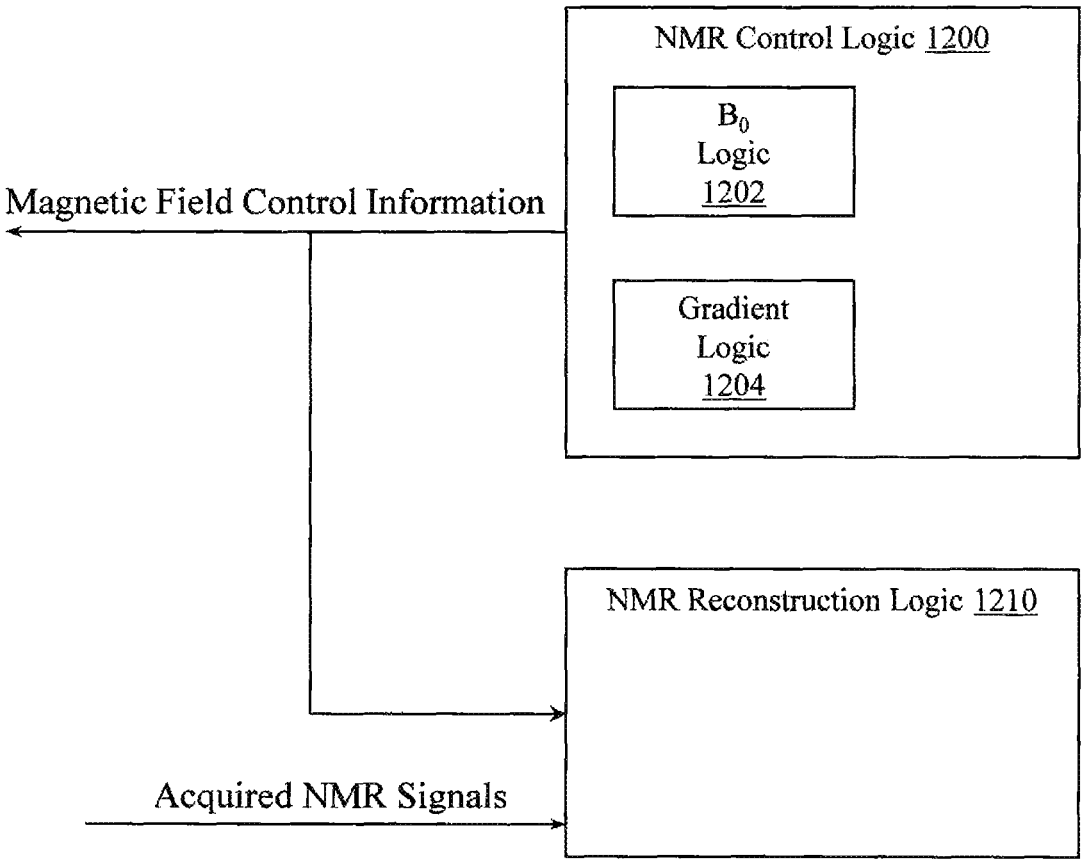
NMR Control Logic 1200
B_0 Logic 1202
Gradient Logic 1204
Magnetic Field Control Information
NMR Reconstruction Logic 1210
Acquired NMR Signals

Figure 12

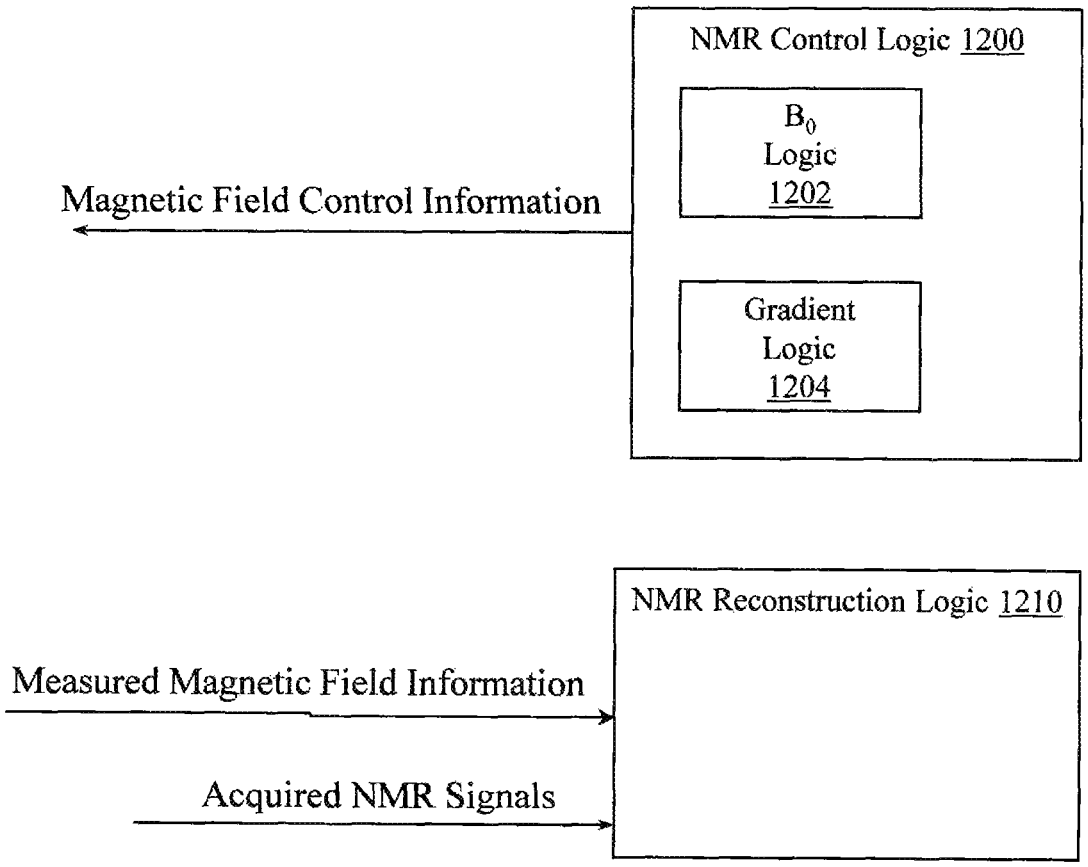
NMR Control Logic 1200
B_0 Logic 1202
Gradient Logic 1204
Magnetic Field Control Information
NMR Reconstruction Logic 1210
Measured Magnetic Field Information
Acquired NMR Signals

Figure 13

WIRELESS MAGNETIC FIELD MONITORING IN MAGNETIC RESONANCE IMAGING

BACKGROUND

Some magnetic resonance imaging (MRI) techniques are pushing MRI apparatus towards their performance limits. Acquisition techniques that operate near the limits may be sensitive to small gradient field perturbations that may create image artifacts. Some conventional MRI acquisitions can successfully rely on a long-standing assumption that the gradient field produced by an MRI apparatus accurately matches the gradient field that was intended to be produced by the MRI apparatus. These conventional MRI acquisitions can rely on the assumption because small field perturbations may be tolerated in image reconstruction. However, some MRI acquisitions that push the MRI apparatus towards their performance limits may not rely on the assumption because even small field perturbations may produce unacceptable artifacts that cannot be tolerated in image reconstruction.

Magnetic field monitoring (MFM) is known to MRI. In theory, MFM can be employed to measure magnetic field perturbations directly and thus can be employed to account for (e.g., correct) artifacts produced by the magnetic field perturbations. While MFM is theoretically able to produce these results, practical implementations of MFM have faced several challenges. For example, conventional MFM has employed a network of miniature MRI coils with highly localized sensitivities to measure the magnetic field evolutions at different spatial locations. If the spatial locations have an appropriate spatial distribution, then the field dynamics can be calculated accurately in an imaging volume. But the network of small coils requires extra cabling, circuitry, and other equipment that may be difficult to accommodate.

Some conventional MFM systems may have relied on an NMR signal from hydrogen to monitor magnetic field dynamics. But for MFM to work, the MFM signal can only come from the local signal source (e.g., MFM probe). If there is any coupling between the MFM signal from different probes in different spatial locations, or if there is any coupling between MFM signal and an NMR signal from an imaging subject, then the MFM system will produce incorrect measurements. Conventional MFM systems may, therefore, have tried to reduce the likelihood of coupling between signals for different probes by spacing probes far apart.

Receive only arrays for MFM have limitations. Therefore, some conventional MFM systems have employed an array of hetero-nuclear transceiver probes to address these limitations. Unfortunately, using an array of hetero-nuclear transceiver probes introduces a requirement for a separate, specialized, multi-frequency transceiver system that is able to acquire, process, and provide the MFM signals from the array of hetero-nuclear transceiver probes.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated in and constitute a part of the specification, illustrate various example systems, methods, and other example embodiments of various aspects of the invention. It will be appreciated that the illustrated element boundaries (e.g., boxes, groups of boxes, or other shapes) in the figures represent one example of the boundaries. One of ordinary skill in the art will appreciate that in some examples one element may be designed as multiple elements or that multiple elements may be designed as one element. In some examples, an element shown as an internal component of another element may be implemented as an external component and vice versa. Furthermore, elements may not be drawn to scale.

FIG. **1** illustrates an example circuit employed in wireless magnetic field monitoring (wMFM).

FIG. **2** illustrates an example circuit employed in wMFM.

FIG. **3** illustrates an example apparatus employed in wMFM.

FIG. **4** illustrates MFM probes interacting with wMFM circuits.

FIG. **5** illustrates MFM probes interacting with wMFM circuits that interact with an MRI apparatus.

FIG. **6** illustrates a wMFM circuit co-located with a conventional wireless coil.

FIG. **7** illustrates a wMFM circuit integrated into a conventional wireless coil.

FIG. **8** illustrates an example method associated with wMFM.

FIG. **9** illustrates an example method associated with wMFM.

FIG. **10** illustrates an MRI apparatus.

FIG. **11** illustrates a portion of an MRI apparatus.

FIG. **12** illustrates a conventional MRI reconstruction logic.

FIG. **13** illustrates an example MRI reconstruction logic.

DETAILED DESCRIPTION

Example apparatus and methods concern wireless magnetic field monitoring (wMFM) in magnetic resonance imaging (MRI). Example apparatus and methods integrate data correction into an MRI reconstruction because the wMFM signal provides information from which the actual field present during an MRI acquisition can be determined as NMR signals intended for reconstruction are acquired.

Resonating nuclei produce NMR signals. These NMR signals can be detected by magnetic resonance (MR) receive coils. Conventionally, MR receive coils were connected to an MRI apparatus by wires or cables or other direct tangible connections. US Patent Publication 2010/0253331 describes receive coils that are "connected" to an MR apparatus using wireless transmissions. Example apparatus and methods may extend the functionality of generic wireless receive coils to accommodate additional MFM functionality. Recall that conventional MFM systems may have required a specialized multi-frequency receiver system. Extending the functionality of generic wireless receive coils that are already present in an NMR apparatus facilitates performing MFM without the additional specialized multi-frequency receiver system.

NMR signals intended for image reconstruction may be received in a receive coil, modulated with a carrier frequency, and then wirelessly provided to the MR apparatus. Example apparatus and methods may configure a receive coil with an additional circuit that is configured to receive MFM signals and to provide those MFM signals to the MR apparatus using wireless transmission. In one embodiment, the MFM signal may be provided to the NMR apparatus in real time, substantially simultaneously with the NMR signals intended for image reconstruction. Thus, example apparatus and methods may be configured to automatically perform image reconstruction using the contemporaneously provided MFM signals.

Spins in a magnetic field precess at a knowable frequency. The frequency is determined by the magnetic field as described by Larmor precession. Larmor precession

describes how the angular momentum vector $\vec{j}$ precesses about the external field axis with an angular frequency:

$$\omega = -\gamma B$$

where ω is the angular frequency, $-\gamma$ is the gyromagnetic ratio, and B is the magnitude of the magnetic field. A spin that is initially precessing at one frequency may precess at a different frequency if the magnetic field changes.

Therefore, spins in an MFM probe can be excited at a first frequency MFM_{F1} determined by a first magnetic field (e.g., B_0). These spins may precess at MFM_{F1} while the first magnetic field remains constant and in place. However, these spins may precess at a second frequency MFM_{F2} if the first magnetic field changes to a second magnetic field. MRI pulse sequences use gradients to change magnetic fields during an acquisition. Therefore, MFM probes excited at an original frequency can provide information about actual magnetic fields being experienced during an image acquisition, where the actual fields are a function of the main magnetic field and the gradient field.

If the magnetic field varies spatially, then the MFM precession frequency will also vary spatially. If the magnetic field varies over time, then the MFM precession frequency will also vary over time. In MRI, magnetic fields are controlled to vary spatially and over time. Therefore, MFM precession frequencies can be tracked spatially and over time to understand the actual magnetic field present. Knowing the actual magnetic field present facilitates accommodating MRI acquisitions that are susceptible to even small perturbations in the magnetic field.

In one example, MFM probes may be configured with fluorine as a resonant species. In one magnetic field, the fluorine may experience nuclear magnetic resonance at 60.1 MHz. Therefore, the fluorine may be excited at 60.1 MHz, the gradient field turned on, and the resulting precession frequency identified in MFM signals acquired from the MFM probes. Since the precession frequency of a resonant species in a first probe is determined by the magnetic field present at the location of the first probe, the detected precession frequency accurately identifies the actual magnetic field present at the first probe. Additionally, the precession frequency of a resonant species in a second probe is determined by the magnetic field present at the location of the second probe. The detected precession frequency accurately identifies the actual magnetic field present at the second probe. While two point determinations associated with two probes are interesting, understanding the relationship between the two point determinations provides additional information.

Consider that a gradient field may be expected to vary in a known way (e.g., linearly) throughout a region. Having data about the actual field present at two points along the path upon which the gradient is to vary linearly facilitates identifying the actual magnetic field present at other points along that path. The magnetic field can be known both instantaneously and as it changes over time.

MFM can calculate magnetic field dynamics. For example the dynamics of a magnetic field B $\{|B(r, t)|\}$ could be examined by measuring the phase evolution $\{\phi(t)\}$ of multiple free induction signal decays at discrete probe locations (r): according to

$$\gamma = \int_0^{\tau} |B(r, r)| \, dt = \varphi(t)$$

FIG. **1** illustrates an example circuit employed in wireless magnetic field monitoring (wMFM). Windings **104** (e.g., copper) are wound around an object **102** (e.g., glass capillary tube) to facilitate transmitting and receiving RF signals. Whether the windings **104** are used for transmitting or receiving is controlled by a transmit/receive switch **106**. When transmitting, the windings **104** may be provided with an RF signal (e.g., 60.1 MHz) from an RF signal source **110**. When receiving, windings **104** may provide a received signal to an analog signal mixer **124**. The received signal may be, for example, 60.1 MHz plus or minus an amount determined by a gradient field. The analog signal mixer **124** may also have available a carrier frequency **120**. The multiplied signal produced by analog mixer **124** may be provided to a filter (e.g., low pass filter **126**) to achieve single sideband modulation. The resulting modulated signal can be wirelessly transmitted through antenna **130**.

FIG. **2** illustrates another example circuit employed in wMFM. This circuit also includes amplifiers **108**, **122**, and **128**. Additionally, this circuit also includes an input path that crosses points **112** and **114**. The input path may receive signals (e.g., control signals, synchronization signals) from an NMR apparatus. This circuit also includes a second input path that crosses points **116** and **118**. This second input path may receive a carrier wave to be used by analog signal mixer **124**. While FIGS. **1** and **2** illustrate two different circuits, one skilled in the art will appreciate that other circuits may be fabricated from different combinations of components that can create NMR excitation in an MFM probe, that can acquire MFM signals from the MFM probe, that can prepare (e.g., modulate) the acquired signal to be wirelessly transmitted to an MRI apparatus, and that can transmit the modulated signal.

Thus, FIG. **3** illustrates more generally an apparatus employed in wMFM. The apparatus includes a transmit/receive coil **204** connected to a transmit/receive control **206**. The transmit/receive control **206** may have available an excitation frequency provided by an excitation frequency provider **210**. The transmit/receive control **206** may also be configured to provide received MFM signals to a modulation logic **224**. The modulation logic **224** is in turn configured to provide the modulated MFM signals to a wireless transmitter **230**.

FIG. **4** illustrates MFM probes **402** and **404** that are positioned in a main magnetic field **400**. The main magnetic field **400** determines the Larmor frequency of the resonant species in the MFM probes **402** and **404**. MFM probe **402** may be excited, for example, by radio frequency energy RF**1** produced by wMFM module wMFM**1** **410**. Similarly, MFM probe **404** may be excited, for example, by radio frequency energy RF**2** produced by wMFM module wMFM**2** **420**. MFM probe **402** may produce MFM signal MFM**1**. The frequency of MFM signal MFM**1** will be determined by the magnetic field present at MFM probe **402**. Similarly, MFM probe **404** may produce MFM signal MFM**2**. The frequency of MFM signal MFM**2** will be determined by the magnetic field present at MFM probe **404**. When the only magnetic field present is main magnetic field **400**, then it is likely that the frequency of MFM**1** and MFM**2** will be the same.

FIG. **4** also illustrates an X gradient coil **430**. X gradient coil **430** can produce a spatially varying gradient magnetic field. Field lines **432** represent the gradient magnetic field. The gradient may cause the overall magnetic field to increase at the top of magnetic field **400** and may cause the overall magnetic field to decrease at the bottom of magnetic field **400**. The increase is illustrated with a positive angle θ between the lines X and X', where X represents the magnetic

field with no X gradient magnetic field and X' represents the magnetic field with the X gradient magnetic field. Similarly, the decrease is illustrated with a negative angle θ between the lines X and X'. MFM probes **402** and **404** report the actual magnetic field at their location. The actual magnetic field can be discerned from the frequencies of MFM**1** and MFM**2**.

FIG. **5** illustrates MFM module wMFM**1** **410** providing a modulated MFM signal modMFM**1** to an MRI apparatus **500**. FIG. **5** also illustrates MFM module wMFM**2** **420** providing a modulated MFM signal modMFM**2** to the MRI apparatus **500**. The modulated MFM signals modMFM**1** and modMFM**2** are provided wirelessly to the MRI apparatus **500**. When coordinated by example apparatus, methods, and circuits described herein, the signals modMFM**1** and modMFM**2** facilitate producing improved MRI images that are less susceptible to gradient field perturbations.

FIG. **6** illustrates a wMFM circuit co-located with a conventional wireless coil **600**. The wireless coil **600** may include an NMR receive circuit **610**, an NMR modulation circuit **620**, and an NMR transmission circuit **630**. Circuits **610**, **620**, and **630** may be configured to receive NMR signals, to modulate the signals for wireless transmission to an MRI apparatus, and to transmit the modulated signals to the MRI apparatus. The wMFM circuit may also include an MFM receive circuit **640**, an MFM modulation circuit **650**, and an MFM transmission circuit **660**. Circuits **640**, **650**, and **660** may be configured to receive MFM signals, to modulate the signals for wireless transmission to the MRI apparatus, and to transmit the modulated MFM signals to the MRI apparatus. Since the circuits are located on the same wireless coil **600**, the circuits may share some infrastructure (e.g., power circuit **670**). While FIG. **6** illustrates two basically separate circuits, some example circuits may be more integrated into a wireless receive coil.

FIG. **7** illustrates a wMFM circuit that is more integrated into a wireless coil **700**. Wireless coil **700** includes an NMR receive circuit **710** for receiving NMR signals from an object to be imaged. The NMR signals that are intended for reconstruction may be provided to an NMR modulation circuit **720** that prepares the signals to be wirelessly transmitted to an MRI apparatus. The prepared signals may be wirelessly transmitted to the MRI apparatus using NMR transmission circuit **730**. Coil **700** may also include an MFM receive circuit **740**. Instead of having separate modulation and transmission circuits, coil **700** may be configured with a single modulation circuit **720** that can process both NMR signals from circuit **710** and MFM signals from circuit **740**. Similarly, transmission circuit **730** may be configured to transmit both NMR signals and MFM signals. In one embodiment, the circuits on wireless coil **700** may be powered by, for example, a single power circuit **770** or may be controlled by, for example, a single control circuit **780**.

While NMR receive circuits **610** and **710** are illustrated, and while MFM receive circuits **640** and **740** are illustrated, in different embodiments, wireless coils may be configured to transmit and receive using the circuits **610**, **710**, **640**, or **740**.

Some portions of the detailed descriptions that follow are presented in terms of algorithms and symbolic representations of operations on data bits within a memory. These algorithmic descriptions and representations are used by those skilled in the art to convey the substance of their work to others. An algorithm is considered to be a sequence of operations that produce a result. The operations may include creating and manipulating physical quantities that may take the form of electronic values. Creating or manipulating a physical quantity in the form of an electronic value produces a concrete, tangible, useful, real-world result.

It has proven convenient at times, principally for reasons of common usage, to refer to these signals as bits, values, elements, symbols, characters, terms, and numbers. It should be borne in mind, however, that these and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to these quantities. Unless specifically stated otherwise, it is appreciated that throughout the description, terms including processing, computing, and determining, refer to actions and processes of a computer system, logic, processor, or similar electronic device that manipulates and transforms data represented as physical quantities (e.g., electronic values).

Example methods may be better appreciated with reference to flow diagrams. For simplicity, the illustrated methodologies are shown and described as a series of blocks. However, the methodologies may not be limited by the order of the blocks because, in some embodiments, the blocks may occur in different orders than shown and described. Moreover, fewer than all the illustrated blocks may be required to implement an example methodology. Blocks may be combined or separated into multiple components. Furthermore, additional or alternative methodologies can employ additional, not illustrated blocks.

FIG. **8** illustrates an example method **800** associated with wMFM. Method **800** includes, at **810**, controlling an NMR apparatus to selectively produce a gradient magnetic field. Different gradient coils can produce different gradient magnetic fields at different times. Therefore, controlling the production of the gradient magnetic field may include controlling a G_X gradient coil, a G_Y gradient coil, or a G_Z gradient coil, alone or in combination. Controlling the NMR apparatus to selectively produce a gradient magnetic field may include, for example, controlling a gradient coil to be turned off, controlling a gradient coil to be turned on, providing an RF excitation signal to the gradient coil, and other actions.

Method **800** also includes, at **820**, controlling the NMR apparatus to cause NMR in resonant species in two or more MFM probes. In one example, the NMR may be caused while the gradient magnetic field is not being produced.

In another example, the NMR may be caused while the gradient magnetic field is being produced. The MFM probes will have been positioned to be affected by the gradient magnetic field. In one example, two MFM probes may be positioned in a line in plane (e.g., slice) to be processed by an MRI apparatus. In another example, the MFM probes may be positioned in a line that intersects several planes (e.g., slices) to be processed by an MRI apparatus. In another example, three MFM probes may be positioned in a plane to be processed by an MRI apparatus. In yet another example, eight MFM probes may be positioned in a cube or sphere arrangement to cover two or more planes (e.g., slices) to be processed by an MRI apparatus. Other numbers of MFM probes may be positioned in other arrangements.

Method **800** also includes, at **830**, controlling the NMR apparatus to acquire MFM signals from the MFM probes while the gradient magnetic field is being produced. Acquiring the MFM signals may include receiving un-modulated MFM signals in a set of receive coils and then processing (e.g., modulating) the un-modulated MFM signals into modulated MFM signals. The modulating may include, for example, single side band modulation, amplitude modulation, frequency modulation, or other modulations.

Once the modulated signal has been produced, the MFM signals may be wirelessly transmitted to the NMR apparatus.

In one example, acquiring the MFM signals may include measuring or characterizing the dynamics of the magnetic field. In this example, method **800** may include measuring the phase evolution $\phi(t)$ of free induction signal decays at locations of the two or more MFM probes according to:

$$\gamma = \int_0^t |B(r_1, r_2)| \, dt = \varphi(t)$$

where: γ is the gyromagnetic ratio, B is the magnetic field, r is a probe location, and Φ is the phase evolution.

Method **800** also includes, at **840**, controlling the NMR apparatus to acquire NMR signals from the object to be processed while the gradient magnetic field is being produced. The acquired NMR signals may be provided to the same NMR apparatus as the MFM signals. Since the NMR signals are acquired contemporaneously with the MFM signals, the MFM signals may be useful to a more accurate reconstruction that is less affected by perturbation artifacts.

Thus, method **800** also includes, at **850**, controlling the NMR apparatus to process the NMR signals based, at least in part, on the MFM signals. In one example, the NMR apparatus is an MRI apparatus and thus the NMR signals are intended to be reconstructed into an image. In this example, processing the NMR signals includes reconstructing an MR image suitable for viewing based, at least in part, on the MFM signals. Thus, processing the NMR signals may include using the MFM signals in a reconstruction.

In one example, the MFM probes may have been configured with a resonant species (e.g., Fluorine) that is not expected to be found in the object to be imaged. This facilitates decoupling MFM signals from NMR signals intended for image reconstruction. While Fluorine is described, it is to be appreciated that different MFM probes may be configured with different resonant species. Additionally, different MFM probes used together in a single MFM procedure may include different resonant species and an MFM probe may be configured with multiple resonant species.

MFM probes may be placed according to a strategy. The strategy may depend, for example, on a property of a receive array to be used to acquire the NMR signals. Even though multiple MFM probes may be positioned and available for excitation, in one example, method **800** may include selectively activating only a desired number of the available probes based, at least in part, on an amount of image correction desired. For example, a first receive array and a first image acquisition may require a first amount of image correction and thus may activate a first number of MFM probes while a second receive array and a second image acquisition may require a second, different amount of image correction and thus may activate a second, different number of MFM probes. With different number of probes being available for selective activation, in one example method **800** may include controlling the NMR apparatus to process the NMR signal in light of the MFM to correct up to first order field perturbation effects in the NMR signal.

FIG. **9** illustrates another embodiment of example method **800**. This embodiment includes actions **810**, **820**, **830**, **840**, and **850** but also includes some initial actions that may be used to calibrate an NMR apparatus or to insure that an MRI apparatus is operating within an acceptable performance range before engaging in an acquisition.

This embodiment of method **800** includes, at **802**, controlling the NMR apparatus to apply a main magnetic field B_0 and then, at **804**, controlling the excitation of an MFM probe by selectively providing RF energy at an excitation frequency. If the main magnetic field B_0 is acceptably uniform and in an acceptable state then MFM probes positioned in the B_0 field ought to be excited and ought to produce the same MFM signals.

This embodiment of method **800** therefore also includes, at **806**, controlling the NMR apparatus to acquire calibration MFM signals from the two or more MFM probes while the main magnetic field B_0 is applied and while the gradient magnetic field is not applied. In one example, acquiring the calibration MFM signals includes receiving un-modulated calibration MFM signals in the set of receive coils and processing the un-modulated calibration MFM signals into modulated calibration MFM signals. Once the modulated calibration signals have been produced, they may then be wirelessly transmitted to the NMR apparatus.

This embodiment of method **800** also includes, at **808**, making a determination concerning whether the calibration MFM signals indicate that the B_0 field is in a desired state. If the determination at **808** is that the B_0 field is not in a desired state, then method **800** may include selectively controlling the NMR apparatus to not collect NMR signals. The determination may be based, for example, on a field parameter (e.g., homogeneity) that may be measured using MFM. While calibrating the B_0 field is described, method **800** may also be employed to selectively produce a gradient magnetic field and then evaluate a property (e.g., homogeneity, linear variance, coverage) of that field. In this example, method **800** includes selectively controlling the NMR apparatus to not engage in an acquisition when a property of the magnetic field falls outside a desired range.

FIG. **10** illustrates an example MRI apparatus **1000** configured with a wMFM apparatus **1099** for performing wireless MFM. The wMFM apparatus **1099** may be configured with elements of example apparatus or circuits described herein or may perform example methods described herein. In one embodiment, apparatus **1099** may provide means for creating NMR in an MFM probe, acquiring MFM signals from the MFM probe, and automatically correcting NMR signals intended for image reconstruction using the MFM signals. The means may include, for example, circuits, programmed logics, and a special purpose computer.

The apparatus **1000** includes a basic field magnet(s) **1010** and a basic field magnet supply **1020**. Ideally, the basic field magnets **1010** would produce a uniform B_0 field. However, in practice, the B_0 field may not be uniform, and may vary over an object being imaged by the MRI apparatus **1000**. MRI apparatus **1000** may include gradient coils **1030** configured to emit gradient magnetic fields like G_S, G_P, and G_R or Gx, Gy, and Gz. The gradient coils **1030** may be controlled, at least in part, by a gradient coils supply **1040**. In some examples, the timing, strength, and orientation of the gradient magnetic fields may be controlled, and thus selectively adapted, during an MRI procedure. Ideally the actual gradient magnetic fields produced would perfectly faithfully represent the desired gradient magnetic fields and would vary perfectly regularly with no perturbations. Since these ideals may not be attained, wMFM is configured to acquire actual magnetic field information.

MRI apparatus **1000** may include a set of RF antennas **1050** that are configured to generate RF pulses and to receive resulting NMR signals from an object to which the RF pulses are directed. In one embodiment, the RF antennas **1050** are arranged as an array of parallel transmission coils that are individually controllable. How the pulses are generated and how the resulting MR signals are received may be

controlled and thus may be selectively adapted during an MR procedure. Separate RE transmission and reception coils can be employed. The RF antennas **1050** may be controlled, at least in part, by a set of RF transmission units **1060**. An RF transmission unit **1060** may provide a signal to an RF antenna **1050**. The RF transmission unit **1060** may provide different signals to different RF antennas to produce different RF excitations from the different members of the array of parallel transmission coils. The RF receive coils may wirelessly provide both NMR signals intended for image reconstruction and NMR MFM signals to, for example, control computer **1070** or wMFM apparatus **1099**.

The gradient coils supply **1040** and the RF transmission units **1060** may be controlled, at least in part, by a control computer **1070**. In one example, the control computer **1070** may be programmed to control an NMR device as described herein. Conventionally, the magnetic resonance signals received from the RF antennas **1050** can be employed to generate an image and thus may be subject to a transformation process like a two dimensional Fast Fourier Transform (FFT) that generates pixilated image data. The transformation can be performed by an image computer **1080** or other similar processing device. The image data may then be shown on a display **1090**. Since the NMR signals intended for reconstruction and the MFM signals describing actual magnetic field conditions are acquired contemporaneously and provided contemporaneously, the reconstruction can proceed with actual magnetic field strength information instead of theoretical magnetic field strength information.

While FIG. **10** illustrates an example MRI apparatus **1000** that includes various components connected in various ways, it is to be appreciated that other MRI apparatus may include other components connected in other ways. Consider the difference between the situations illustrated in FIGS. **12** and **13**. In FIG. **12** an NMR control logic **1200** has a B_0 logic **1202** and a gradient logic **1204**. Conventionally, the B_0 logic **1202** would provide information for controlling the B_0 field and the gradient logic **1204** would provide information about controlling gradient magnetic field(s). This information would be provided both to circuits that control magnetic field production and to NMR reconstruction logic **1210**. In FIG. **13**, NMR control logic **1200** still provides the B_0 information and the gradient magnetic field information. However, instead of the NMR reconstruction logic **1210** relying on the control information, the NMR reconstruction logic **1210** relies on actual magnetic field information measured and provided by wMFM systems, apparatus, circuits, or methods. Since the reconstruction depends on information about the magnetic field, the NMR reconstruction logic **1210** in FIG. **13** may produce superior results to that of FIG. **12**.

Thus, apparatus **1000** may be part of an MRI system that includes a plurality of wireless MFM modules that are configured to receive MFM signals from a plurality of MFM probes and to wirelessly transmit modulated MFM signals produced from the received MFM signals. Apparatus **1000** may also include a wireless receiver that is configured to receive the wirelessly transmitted modulated MFM signals and to process the modulated MFM signals into magnetic field measurement information. The magnetic field measurement information can then be made available for real-time reconstruction of an MRI signal. Therefore, apparatus **1000** may include an MRI reconstruction logic in, for example, wMFM apparatus **1099** or image computer **1080**. The MRI reconstruction logic may be configured to produce an MR image from the MRI signal based, at least in part, on the magnetic field measurement information rather than from presumed magnetic field information.

Since MFM signals are to be acquired in a time frame relevant to the acquisition of NMR signals from which MRI images can be reconstructed, apparatus **1000** may also include a synchronization logic that is configured to synchronize MFM probe excitation, MFM signal acquisition, and, an NMR pulse sequence associated with acquiring MRI signals intended for image reconstruction.

FIG. **11** illustrates an embodiment of a wireless MFM apparatus **1099**. Apparatus **1099** may be a computer, electronic, or other apparatus that is configured to control an MRI apparatus (e.g., apparatus **1000**) to produce, acquire, or use MFM information. Apparatus **1099** may include an excitation logic **1110** that is configured to control excitation of a resonant species in an MFM probe. Controlling excitation may include controlling an RF signal source that produces an RF signal for exciting an MFM probe and controlling a transmit coil that applies the RF signal to the MFM probe.

Apparatus **1099** may also include an acquisition logic **1120** that is configured to control acquisition of MFM signals produced by the excited MFM probe. Controlling acquisition may include controlling a receive coil. Controlling the receive coil may include, for example, tuning the receive coil to a resonant frequency associated with an MFM probe. The receive coil receives an MFM signal from an MFM probe.

Apparatus **1099** may also include a provision logic **1130** that is configured to provide the MFM signals to an apparatus that will process contemporaneously acquired NMR signals intended for reconstruction. The provision logic **1130** may control a modulator that is configured to input the MFM signal received by receive coil and to output a modulated MFM signal. In one example, the modulator may be an analog signal mixer that encodes the MFM signal using a carrier frequency and modulation techniques including, but not limited to, single side band modulation, amplitude modulation, frequency modulation, and frequency division modulation. The provision logic **1130** may also control a transmitter that is configured to wirelessly provide the modulated MFM signal.

Apparatus **1099** may also include a control logic **1140** that is configured to control the operations of logic **1110**, **1120**, and **1130**. Controlling the logics may include coordinating their activity with that of the MRI apparatus. For example, the MFM probes may be excited at one point in an acquisition and then may be listened to during another point(s) in the acquisition.

In one embodiment, apparatus **1099** may be a circuit that is located on a receive coil in an NMR apparatus. In another embodiment, apparatus **1099** may be a circuit operably connected to and sharing at least one component with a wireless receive coil in an NMR apparatus. While separate receive coils and transmit coils are described, one skilled in the art will appreciate that in one embodiment the receive coil and the transmit coil may be the same coil. When the same coil can function as both the transmit and receive coil, apparatus **1099** may also include a transmit/receive switch that is configured to selectively control whether the wMFM apparatus is in a transmit mode or a receive mode. In one embodiment, the transmit/receive switch may be controllable by an NMR apparatus to facilitate coordinating MFM probe excitation and MFM signal acquisition with an MRI pulse sequence configured to produce NMR signals intended for reconstruction.

While example systems, methods, and other embodiments have been illustrated by describing examples, and while the examples have been described in considerable detail, it is not the intention of the applicants to restrict or in any way limit the scope of the appended claims to such detail. It is, of course, not possible to describe every conceivable combination of components or methodologies for purposes of describing the systems, methods, and other embodiments described herein. Therefore, the invention is not limited to the specific details, the representative apparatus, and illustrative examples shown and described. Thus, this application is intended to embrace alterations, modifications, and variations that fall within the scope of the appended claims.

The following includes definitions of selected terms employed herein. The definitions include various examples or forms of components that fall within the scope of a term and that may be used for implementation. The examples are not intended to be limiting. Both singular and plural forms of terms may be within the definitions.

References to "one embodiment", "an embodiment", "one example", "an example", and so on, indicate that the embodiment(s) or example(s) so described may include a particular feature, structure, characteristic, property, element, or limitation, but that not every embodiment or example necessarily includes that particular feature, structure, characteristic, property, element or limitation. Furthermore, repeated use of the phrase "in one embodiment" does not necessarily refer to the same embodiment, though it may.

"Computer-readable medium", as used herein, refers to a non-transitory medium that stores signals, instructions or data. A computer-readable medium may take forms, including, but not limited to, non-volatile media, and volatile media. Non-volatile media may include, for example, optical disks, magnetic disks, and other disks. Volatile media may include, for example, semiconductor memories, dynamic memory, and other memories. Common forms of a computer-readable medium may include, but are not limited to, a floppy disk, a flexible disk, a hard disk, a magnetic tape, other magnetic medium, an ASIC, a CD, other optical medium, a RAM, a ROM, a memory chip or card, a memory stick, and other media from which a computer, a processor or other electronic device can read.

"Logic", as used herein, includes but is not limited to hardware, firmware, software in execution on a machine, or combinations of each to perform a function(s) or an action (s), or to cause a function or action from another logic, method, or system. Logic may include a software controlled microprocessor, a discrete logic (e.g., ASIC), an analog circuit, a digital circuit, a programmed logic device, a memory device containing instructions, and other devices. Logic may include one or more gates, combinations of gates, or other circuit components. Where multiple logical logics are described, it may be possible to incorporate the multiple logical logics into one physical logic. Similarly, where a single logical logic is described, it may be possible to distribute that single logical logic between multiple physical logics.

An "operable connection", or a connection by which entities are "operably connected", is one in which signals, physical communications, or logical communications may be sent or received. An operable connection may include a physical interface, an electrical interface, or a data interface. An operable connection may include differing combinations of interfaces or connections sufficient to allow operable control. For example, two entities can be operably connected to communicate signals to each other directly or through one or more intermediate entities (e.g., processor, operating system, logic, software). Logical or physical communication channels can be used to create an operable connection.

"Signal", as used herein, includes but is not limited to, electrical signals, optical signals, analog signals, digital signals, data, computer instructions, processor instructions, messages, a bit, a bit stream, or other means that can be received, transmitted or detected.

"User", as used herein, includes but is not limited to one or more persons, software, computers or other devices, or combinations of these.

To the extent that the term "includes" or "including" is employed in the detailed description or the claims, it is intended to be inclusive in a manner similar to the term "comprising" as that term is interpreted when employed as a transitional word in a claim.

To the extent that the term "or" is employed in the detailed description or claims (e.g., A or B) it is intended to mean "A or B or both". When the applicants intend to indicate "only A or B but not both" then the term "only A or B but not both" will be employed. Thus, use of the term "or" herein is the inclusive, and not the exclusive use. See, Bryan A. Garner, A Dictionary of Modern Legal Usage 624 (2d. Ed. 1995).

To the extent that the phrase "one or more of, A, B, and C" is employed herein, (e.g., a data store configured to store one or more of, A, B, and C) it is intended to convey the set of possibilities A, B, C, AB, AC, BC, or ABC (e.g., the data store may store only A, only B, only C, A&B, A&C, B&C, or A&B&C). It is not intended to require one of A, one of B, and one of C. When the applicants intend to indicate "at least one of A, at least one of B, and at least one of C", then the phrasing "at least one of A, at least one of B, and at least one of C" will be employed.

What is claimed is:

1. A non-transitory computer-readable storage medium storing computer executable instructions that when executed by a computer, control the computer in order to perform a method of reconstructing a magnetic resonance image, comprising:

controlling a nuclear magnetic resonance (NMR) apparatus in order to selectively produce a gradient magnetic field, where the NMR apparatus is specifically an MRI apparatus;

controlling, during an MRI image acquisition, the NMR apparatus with the computer in order to cause NMR to occur in a resonant species of an object that is within a pre-determined distance of a plurality of magnetic field monitoring (MFM) probes, the plurality of MFM probes being positioned in order to be affected by the produced gradient magnetic field, where the plurality of MFM probes, has at least 8 MFM probes that are positioned in either a cube arrangement or a spherical arrangement in order to cover two or more MRI slice planes

controlling, during the MRI image acquisition, the NMR apparatus in order to acquire MFM signals from the plurality of at least 8 MFM probes while the gradient magnetic field is being produced, where acquiring the MFM signals comprises:

receiving un-modulated MFM signals with a set of receive coils;

processing the received un-modulated MFM signals into modulated MFM signals, where processing the un-modulated MFM signals into modulated MFM signals comprises performing with the computer an amplitude modulating and a frequency division modulating of the received un-modulated MFM signals, and

wirelessly transmitting the Amplitude and frequency division modulated MFM signals to the NMR MRI apparatus;

controlling the NMR apparatus substantially simultaneously with the wireless transmission of the Amplitude and frequency division modulated MFM signals to the NMR apparatus, in order to acquire NMR signals from an object undergoing an MRI scan while the gradient magnetic field is being produced, where the NMR signals are then reconstructed into a magnetic resonance image;

controlling the NMR apparatus with the computer in order to process the acquired NMR signals with the MFM signals, where processing the NMR signals includes reconstructing an MR image that is suitable for viewing from the MFM signals; and

displaying the reconstructed MR image.

2. The non-transitory computer-readable storage medium of claim **1**, comprising measuring the phase evolution $\phi(t)$ of free induction signal decays at locations of the plurality of at LEAST 8 MFM probes according to:

$$\gamma = \int_0^{\tau} |B(r_1, r_2)|\, dt = \varphi(t)$$

where:

γ is the gyromagnetic ratio,

B is the magnetic field,

r is a probe location, and

Φ is the phase evolution.

3. The non-transitory computer-readable storage medium of claim **1** comprising configuring the MFM probes with a resonant species that is not expected to be found in the object that is being imaged by the MRI apparatus.

4. The non-transitory computer-readable storage medium of claim **1**, where the gradient magnetic field is produced by one or more of, a G_x gradient coil, a G_y gradient coil, and a G_z gradient coil.

5. The non-transitory computer-readable storage medium of claim **1**, the method comprising:

controlling the NMR apparatus with the computer in order to apply a main magnetic field B_0; and

controlling the NMR apparatus in order to acquire calibration MFM signals from the plurality of at least 8 MFM probes while the main magnetic field $B_0$is applied and while the gradient magnetic field is not applied, where acquiring the calibration MFM signals comprises:

receiving un-modulated calibration MFM signals with the set of receive coils;

processing the un-modulated calibration MFM signals into modulated calibration MFM signals by performing amplitude and frequency modulation, and

wirelessly transmitting the modulated calibration MFM signals back to the NMR apparatus.

6. The non-transitory computer-readable storage medium of claim **5**, comprising selectively controlling the NMR apparatus with the computer in order to not collect NMR signals upon determining that the calibration MFM signals indicate that a magnetic field property exceeds an acceptable threshold.

7. The non-transitory computer-readable storage medium of claim **1**, comprising

selectively activating a desired number of the plurality of at least 8 MFM probes based, on an amount of image correction desired.

8. The non-transitory computer-readable storage medium of claim **1**, where MFM signals are used in order to correct first order field perturbation effects in the NMR signal.

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